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# Heavy ion inertial fusion in Europe

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**Abstract**

Completion of the HIDIF-study in 1998 has been an important step in our understanding of critical issues of the RF-Linac/Storage Ring approach to heavy ion fusion pursued in Europe. One of the conclusions from this study was that the upgradability of the HIDIF-scheme to drive high-gain targets (for energy production) would benefit from an efficient reduction of the total beam phase space volume by a suitable non-Liouvillian technique. The implementation of an effective non-Liouvillian technique suitable for heavy ions is discussed in the context of the "Next Generation Facility" at GSI, which is understood as a significant extension of the present accelerator. Our studies have shown that $Xe^{47+}$ stripping foil injection into a high-current accumulator ring could produce bunches of several tens of kilojoules. We also discuss the perspectives of using photo-ionization stripping in an upgraded HIDIF driver. © 2001 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

For the studies on heavy ion driven inertial fusion in the European Community an important focus has been the HIDIF scheme [1] terminated in 1998. It has been carried out within the framework of a European Study Group in the years 1994–98. Collaborators in the field of the accelerator have been individuals from GSI, CERN, Rutherford, Frankfurt University (IAP) and FZ Juelich. On the target and reactor side collaborators have been from Frascati, Madrid, Moscow, Munich and FZ Karlsruhe. Its scope has been to demonstrate the feasibility of an RF linac and storage ring based scheme for high repetition rate ignition consistent with an indirectly driven low-gain target [2–4].

For the near-term as well as intermediate-term development in this field the existing as well as planned future facilities at GSI play an equally important role. In this context, the HIDIF-study has been useful to identify areas, where enhanced research is necessary, like non-Liouvillian methods or bunch compression. The present understanding (outlined in Fig. 1) is that the development of the GSI nuclear physics facilities, and in parallel relevant accelerator experiments and theory will play a central role in the advancement of this field. Here the main emphasis is on the generation, accumulation and compression of high currents of heavy ions like $U^{28+}$. In spite of the relatively modest funding level the dual usage enables visible progress in this field. This can be expected equally for the intended upgrade of the GSI facility. Obviously, specific developments for heavy ion fusion need to be carried out as well, which take into account problems emerging from the low

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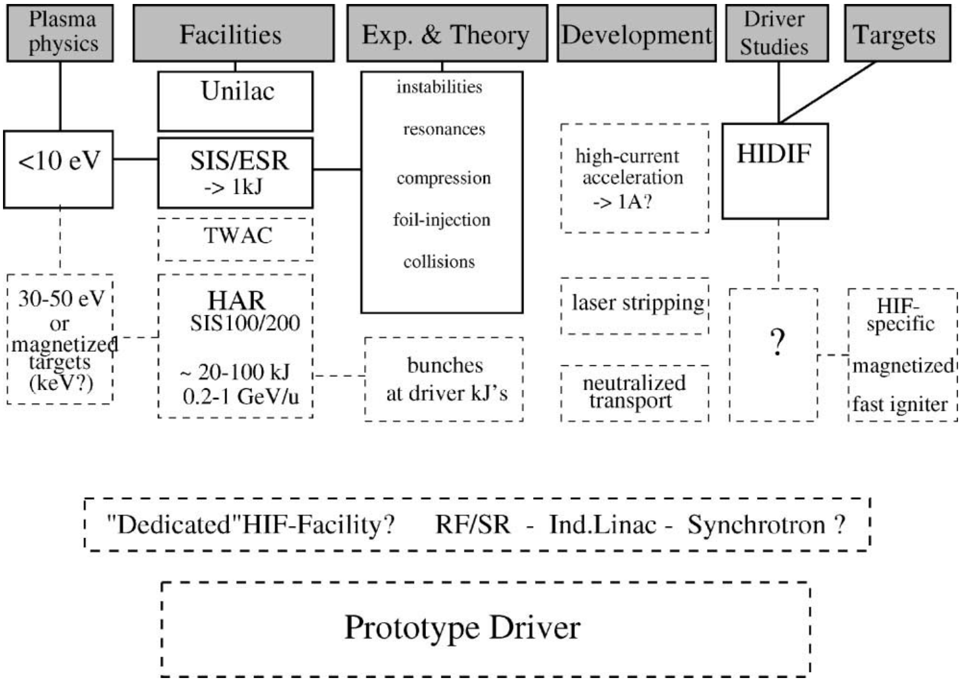


Fig. 1. Overview on the GSI approach to heavy ion fusion development.

charge states and extremely high beam currents. Plasma physics experiments are entering the range of 1–10 eV temperatures with the new intensity upgrade, and are expected to move to 30–50 eV for the next-generation facility. A new development of the past two years has been the start of the PHELIX Petawatt laser system which promises a fruitful synergism between photons and heavy ions. For future upgrades of the HIDIF study, the development of more heavy-ion-specific target schemes remains a crucial issue. An interesting development goes into the direction of designs with lower ablator temperature and longer pulse duration up to 20 ns [5]. Symmetry issues in more spherical illumination geometry have been studied [6] as an interesting alternative, provided that the reactor implications of beams in such a geometry can be solved.

## 2. Conclusions to be drawn from the HIDIF-study

The detailed design of several key components of the driver accelerator has led to a number of important conclusions, which are relevant for future work. It has appeared desirable that the knowledge gained by this work should be applied to an upgrade of the HIDIF-driver for high-gain targets for energy production. It was estimated that high-gain targets at 10 GeV would require at least 10 MJ of total energy, or alternatively at 5 GeV for an energy of about 5 MJ. The latter appears favorable for the target and allows a reduced length of the linac, at the price of increasing the load (in terms of space charge issues) on the storage rings and final compression and transport. An effective balance between cost and feasibility remains to be carried out in the future. In the following we summarize the main conclusions.

- *Target*. A lower kinetic energy (shorter range) would be favorable from the target point of view, and 5 GeV Bi ions with a total energy of 5–6 MJ seemed an option worth to pursue. The two-converter target concept by Ramis was modified to a high-gain ($G = 100$) version requiring 5 MJ energy, spot radius of 5 mm and pulse length of the main pulse up to 20 ns [5]. The choice of longer pulse length was possible due to a lowered peak temperature in the capsule ablator [7]. A spherical hohlraum with 6 MJ and $G = 78$ was developed by Basko employing a P4 illumination geometry with beams in 4 cones at $\pm 20^0$ and $\pm 60^0$ and a focal spot of 6 mm [8]. It needs to be studied how such a beam arrangement can be reconciled with reactor considerations.

- *Driver efficiency and rep-rate*. The HIDIF driver can in principle be rep-rated up to 50 Hz (provided that beam activation is under control). Therefore the goal of single-shot ignition appeared to be inadequate for this approach. This "free" repetition rate is largely due to the power "de-concentration" in the relatively complex accelerator scenario. Linac repetition rates of 10–20 Hz with several reactor chambers are favorable to the driver efficiency (desirable as close as possible to 20%, see also Ref. [9]), and to the impact of driver capital cost on the cost of electricity. This has been already recognized in the HIBALL study [10].
- *Beam spill*. Realization of a low-spill injection into the storage ring was identified as the most stringent bottleneck. The new method of two-plane multi-turn injection (20 turns) was optimized for this purpose. We required to keep beam spill on the injection septum at the level of 1% to keep nuclear activation at such low level that hands-on maintenance would not become impossible. Although the activation by heavy ions at 50 MeV/$u$ is strongly reduced (compared with 1 GeV protons) due to the short Coulomb stopping range, experimental data in this energy range are not available and the assumed 1%-level tolerance is only a first guess.
- *Final compression*. The choice of induction buncher linacs with multiple beams (24) was an option considered to cope with the short distance of about 300 m over which the bunch rotation (in phase space) had to be carried out. For an upgrade it is desirable to replace the linear induction compressor scheme by a compressor ring.
- *Efficient non-Liouvillian technique*. The relatively large number of final beam lines to the chamber could be reduced by a factor three due to the non-Liouvillian bunch merging in phase space by "telescoping", hence only 48 beam lines would be aiming at the target. For the more demanding upgrade to energy production, it seems necessary to enhance this "non-Liouvillian" gain factor considerably in order to reduce the beam line complexity following the storage ring extraction. A possible option is photo-ionization stripping by an intense laser beam as will be discussed later in this paper.

## 3. Development at GSI

### 3.1. Intensity upgrade

This development emerged from the needs of the nuclear physics community for higher event rates and is highly beneficial for fusion driver studies and plasma physics. The new front end of the UNILAC consists of a 34 MHz RFQ and I-H structure to replace the old injector up to the stripping energy of 1.4 MeV/$u$. It accelerates ions with $A/q$ up to 65 and intensities up to 0.25 $A/q$ mA to the energy of 1.4 MeV/$u$, where they are stripped and further accelerated in the Alvarez structure (see Ref. [11]). The corresponding currents of 15 mA of $U^{4+}$ are produced by a new metal vapor source as described in Ref. [12]. This leads to 10 mA $U^{28+}$ after stripping and an expected intensity of $10^{11}$ ions in the SIS. This will eventually raise the available bunch energy to about 1 kJ at 200 MeV/$u$.

### 3.2. Pulse compression prototype cavity

The compression of pulses to the length of typically 10 ns in a driver requires cavities with high gradient, and at the same time, a low operating frequency, which is determined by the initial pulse length. For the frequencies of a few MHz, vacuum cavities would have huge dimensions and it is necessary to reduce their size by filling with high permeability magnetic material.

A prototype of a metallic alloy ("Vitrovac") cavity (see Ref. [13]) is presently designed at GSI,

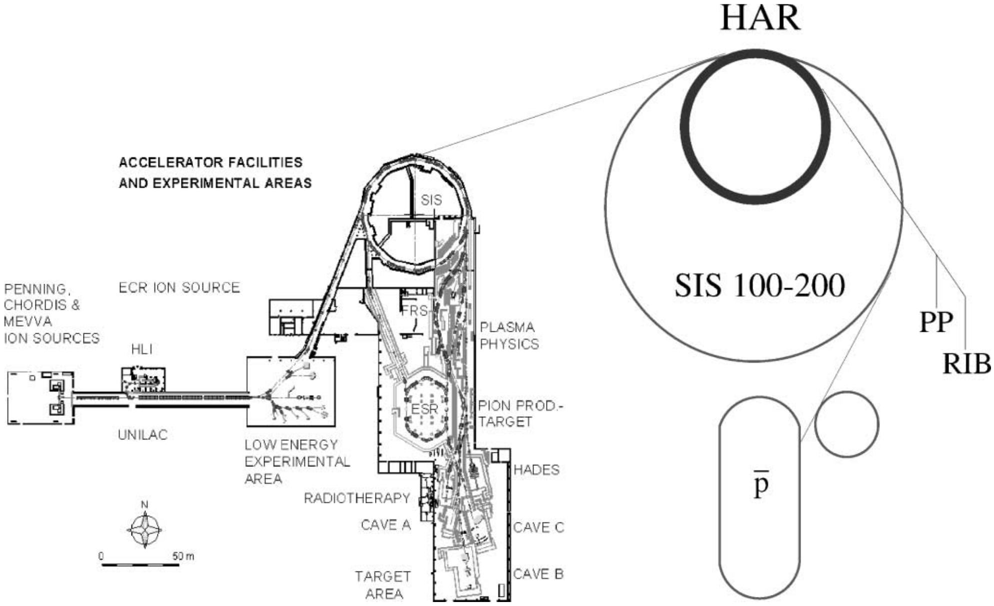


Fig. 2. Schematic view of presently discussed next-generation facility at GSI based on a large synchrotron for radioactive and secondary beams and HAR option.

which allows compression of the expected 1 kJ pulses of $U^{28+}$ to the final length of about 50 ns. It is designed to deliver 200 kV amplitude at 0.8 MHz (corresponding to the revolution frequency of $U^{28+}$ at 200 MeV/$u$), whereas the existing cavities only allow 32 kV.

### 3.3. Beam instabilities in circular machines

The issue of longitudinal instabilities driven by resistive impedances has continued to be an interesting and challenging subject with application to IFE, but also to other presently discussed uses of high-power accelerators (proton machines for spallation neutrons, neutrinos etc.). Using a direct Vlasov solver simulation code, new insight could be gained into the long-term evolution of a beam which had gone through an unstable phase (see Ref. [14]).

### 3.4. Studies on a next-generation accelerator at GSI

The ongoing studies on the next-generation-facility at GSI have their main goals in the areas of radioactive beams (RIB), secondary beams (anti-protons) and medium energy nuclear collisions. Plasma physics/IFE are considered as promising applied research goals in this context. The main facility will be a 100–200 Tm synchrotron, supplemented by several rings and experimental areas for RIB's and anti-proton physics (see Fig. 2).

A high-current accumulation and compression ring "HAR" is presently a part of the discussion in a dual function as accumulator and stretcher ring for RIB and plasma physics. While the final choice of scenario (including the HAR) still requires further iteration, we discuss here the potential of such a ring for plasma physics/IFE, which could open a new realm of intensities ($> 10^{12}$ ions) and beam power beyond the existing capabilities at GSI.

A preliminary draft is shown in Fig. 3. A main feature of this proposal is accumulation by non-Liouvillian stripping of heavy ions by means of a 15 mg/cm$^2$ foil made of tantalum. In this option, bunches of $Xe^{47+}$ could be accelerated in the SIS and accumulated by non-Liouvillian stacking of 5–10 batches into the HAR using foil stripping of $Xe^{47+}$ to $Xe^{54+}$ at 1100 MeV/$u$ (an idea first

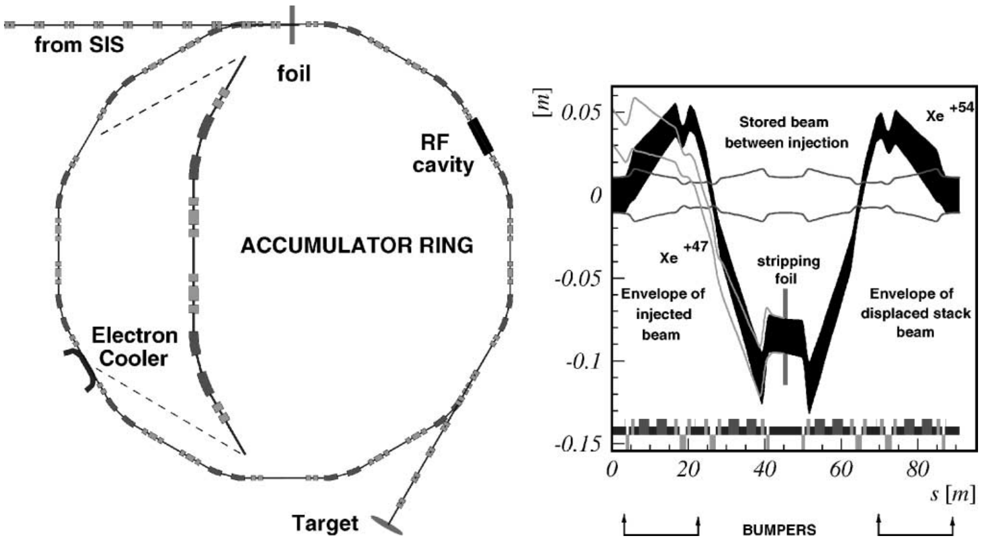


Fig. 3. Schematic view of preliminary design of a HAR with non-Liouvillian foil stacking of several bunches of $Xe^{47+}$ into a common phase space for $Xe^{54+}$.

proposed in Ref. [15]). The kinetic energy is chosen such that bare ions are in an equilibrium with the foil and repeated crossing of stripped and stacked ions through the foil is tolerable. Note that the method proposed here can be carried out in less than 10 s and foresees that all following bunches are merged into the phase space of the first bunch ("central injection" with respect to foil). An alternative is painting a larger number of turns by applying an orbit bump as is usually done for $H^-$ injection; painting is also proposed for the TWAC-project using $Co^{27+}$ or lighter ions [16].

The new high-current injector can be expected to deliver 14 emA (electrical mA) of $Xe^{47+}$, with 8 pmA (particle mA) of $Xe^{2+}$ from a Cordis-source, stripped to 1.2 pmA of $Xe^{21+}$ at 1.4 MeV/$u$ and to 0.3 pmA at 11 MeV/$u$. The final compression from 500 ns (after stacking) to 30–50 ns pulse length leads to a significant transverse space charge effect, which would model the final compression in a full driver compression scheme.

### 3.5. Performance estimates for foil stacking

For plasma physics experiments with cylindrical target geometry, the total kilojoules deposited in the target are a relevant figure of merit, in particular if hydrodynamic expansion or heat conduction is suppressed as in magnetized targets [17]. Independent of the actual size of the accelerator it is possible to express the energy $E \times (kJ)$ stored in a coasting beam in terms of the Laslett tune shift $\Delta Q$ according to

$$E(kJ) \propto \Delta Q \varepsilon \beta^2 \gamma^3 (A/q)^2 E_{\mathrm{kin}}, \tag{1}$$

where $\varepsilon$, the emittance; $A/q$, the mass to charge ratio; and $E_{\mathrm{kin}}$, the ion kinetic energy per nucleon. Assuming a reference emittance (filled by the foil stacking procedure with additional painting) of $50\pi$ mm mrad we readily obtain $62 \times \Delta Q/0.05$ kJ for $^{131}Xe^{54+}$ at 1100 MeV/$u$ and $14 \times \Delta Q/0.05$ kJ for the lighter $^{59}Co^{27+}$ ion at 700 MeV/$u$, where both ions have the same range in matter (the latter is considered in the TWAC-project, see Ref. [16]). These numbers have to be reduced in proportion to a bunching factor if the beam is in a bucket during stacking. Assuming the same $\Delta Q$, it is seen that the heavier ion leads to a superior performance. The actually achievable $\Delta Q$ depends on the stacking speed. As a guideline it may be assumed that for stacking over a few seconds a $\Delta Q/0.05 \approx 1$ is not unrealistic if the working point is moved to a region in the tune diagram free of third and fourth order error resonances. For significantly longer storage times it may be necessary to reduce $\Delta Q/$ 0.05 further in order to eliminate fifth order resonances. For extended storage times intra-beam scattering may lead to momentum heating and further reduce the performance. In any case an intensity of several tens of kJ of heavy ions would be a major milestone in heavy ion fusion driver development and possibly lead to the edge of fusion neutron production in an imploding magnetized target [18].

A test of the foil-stripping method appears possible in the SIS using a $C^{4+}$ beam at injection energy of $11\,\mathrm{MeV}/u$ with a C-foil of $50\,\mu\mathrm{g/cm}^2$. First estimates suggest that it is possible to exceed the usual injection limit by a noticeable factor and thus carry out space charge studies which would otherwise not be possible.

### 3.6. Dense plasma physics

Experiments in this field can be divided into two categories: fundamental studies of dense plasmas (see overview in Ref. [19]) and applications to transport and focusing. In heavy ion energy loss experiments with the 100 J nhelix laser, a new result is the increased equilibrium charge state distribution measured for very dense plasmas [20]. Conditions are now studied to prepare experiments making use of the high-current upgrade of the accelerator, which is expected to become fully effective in 2001. This also includes hollow cylinder shaped ion beams, which have been produced with a specially tailored plasma lens [21]. Transport of ion beams over several meters without any guiding structures like tubes or wires is crucial for IFE target chambers. In the experiment at GSI a vacuum chamber of 50 cm length filled with ammonia gas of 10–20 mbar was used to create the discharge channel, and a C ion beam at $13.6\,\mathrm{MeV}/u$ from the UNILAC accelerator was guided through the chamber using a differential pumping system [22].

### 3.7. PHELIX project

The recently started PHELIX project will supplement the high-intensity heavy-ion beams available in the near future at GSI by the installation of a kJ/pW laser system [23]. Essential for a wide applicability of this laser system is its versatility in the temporal duration of the laser pulses. It is therefore planned to build a laser system that can be operated as a kJ laser with either nanosecond or sub-picosecond pulses. The project is in collaboration with the Lawrence Livermore National Laboratory and the Max Born Institute in Berlin. The laser and the heavy-ion beams can be used to produce and diagnose plasmas in combination, which promises unique experimental possibilities.

## 4. Non-Liouvillian accumulation technique for HIDIF

One of the crucial issues of an RF accelerator driver is the inevitable degradation of phase space density from the source to the target as a direct consequence of Liouville's theorem. Non-Liouvillian foil stripping as means to counteract this is not feasible since we need to conserve the low charge state because of space charge reasons.

A technically still very challenging technique suitable for single charged heavy ions is the use of photo-ionization stripping. In analogy to the foil stripping of $H^-$ for intense proton machines, it has been proposed to apply photo-ionization stripping injection into the storage rings of heavy ion fusion drivers [24,25], or alternatively for final bunch accumulation [26]. We return here to the latter idea, since storage of the double-charged ions for several ms seems less attractive for space charge and stability reasons. Some basic considerations are presented here, whereas full incorporation of such a scheme into HIDIF remains to be carried out in the future.

### 4.1. Photon requirements

The cross-sections for direct ionization are as low as $10^{-18}$–$10^{-17}\,\mathrm{cm}^2$, hence it is more promising to consider autoionization, which can have cross-sections of the order of $10^{-15}\,\mathrm{cm}^2$. Such cross-sections have been measured for $Ba^+$ [27]; recent calculations have indicated that for $Bi^+$ similar cross-sections can be expected for 25 eV photons [28]. In this case, the photon "target thickness" required for 90% conversion into 2+ is typically $5 \times 10^{15}\,\mathrm{cm}^{-2}$. For photon energies between 20 and 30 eV such parameters are coming close to realization with the new TESLA Test Facility free electron laser at DESY, which is expected to come into operation in the near future [29]. It is based on the first section of the TESLA electron linac up to 300 MeV with a 14 m long undulator. The 0.7 ms long RF pulse should produce 10 kW of light with 7000 equidistant micro-pulses containing $2 \times 10^{14}$ photons each, hence several such micro-pulses appropriately timed would suffice for single-pass stripping.

### 4.2. Stripping accumulation scheme

The technical implications and the consequences on beam quality of such a scheme are not trivial. So far, we have investigated a first draft of a storage ring environment, which would allow to accumulate in a non-Liouvillian way several of the HIDIF bunches into a single bunch. We estimate that a factor of 5–10 accumulation might be feasible, which would imply an equivalent reduction in complexity of the final beam switch-yard and focusing system.

Stripping of the heavy ion beam during a single passage through an interaction region with the photons requires a typical length of ≈10 m and a transverse size compression to ≈1 cm radius, both of which are necessary to reduce the power requirement of the photon beam to the above estimated value. For our draft, we have considered 5 GeV $Bi^{+}$ ions and re-designed the HIDIF storage rings with a two-fold symmetry rather than the original three-fold, which helps to reduce the ring circumference. The stripping interaction region is in a by-pass of the storage ring switched by a kicker magnet. Each of the rings is filled with an equal number of bunches (typically 12 or higher). The stripping accumulation scheme in the $n$th storage ring is shown schematically in Fig. 4 and requires three steps:

(1) a bunch of $Bi^{++}$ from a preceding stripping accumulation in the $(n-1)$th ring arrives synchronously with a $Bi^{+}$ bunch yet unstripped and kicked into the by-pass;
(2) both bunches overlap in the interaction region, where the $Bi^{+}$ is stripped whereas the original $Bi^{++}$ remains unaffected by the photons;
(3) the combined single bunch is transferred to the $(n+1)$th storage ring, where the process is repeated.

Fig. 5 shows details of the lattice of such a low-beta (2.5 m average beta function) interaction region, which has to compress the beam to the small size and match it to the ring lattice. The undulator-like interaction region consists of densely packed super-conducting quadrupoles

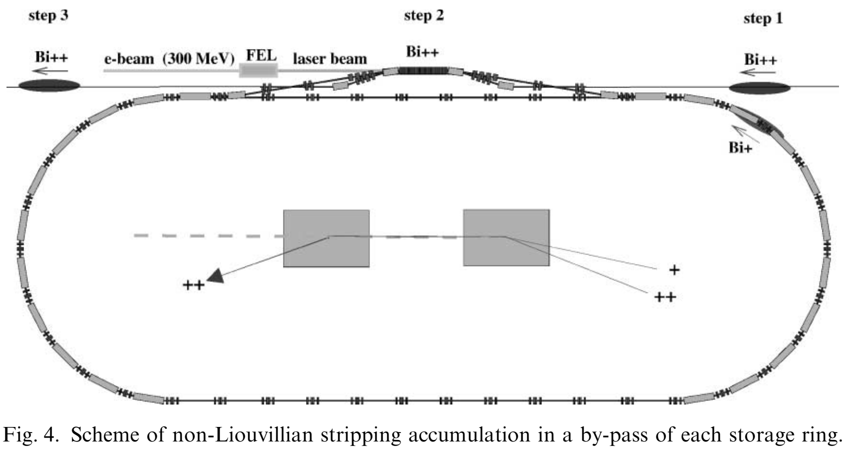


Fig. 4. Scheme of non-Liouvillian stripping accumulation in a by-pass of each storage ring.

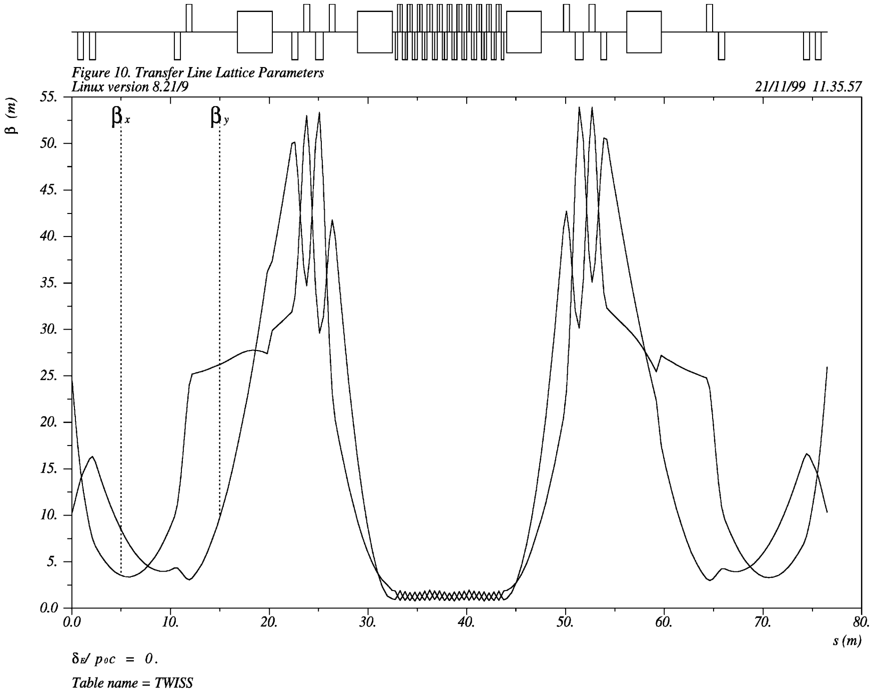


Fig. 5. Lattice for 10 m long low-beta photon-heavy ion interaction region.

with approximately 5 T pole tip field. The bunch intensity after $N$ accumulation steps is thus multiplied by $N$, whereas the phase space volume remains ideally unchanged. Due to the inevitable mismatch of $Bi^{+}$ and $Bi^{++}$ in the interaction region and space charge effects a certain amount of emittance growth must be expected, which requires detailed simulation studies. After bunch accumulation it is envisaged to transfer the remaining number of bunches into a compressor ring for final bunch compression. Obviously the increased charge state as well as bunch intensity in this final bunch compression require careful future studies. It is foreseeable that neutralization during chamber transport is necessary under such extreme space charge conditions.

## 5. Conclusions

The HIDIF driver study has provided a useful basis to guide further research on targets and accelerators. The possibility of advancing the understanding of accelerators by dual use with a next-generation facility at GSI appears as a unique opportunity for heavy ion fusion driver development, before a dedicated facility (RF or induction technology based) can be envisaged in some future. Our estimates lead to the conclusion that foil stripping, if successfully demonstrated, could lead into a parameter region for heavy ion bunches, which is of driver relevance—without large additional investment for the next-generation facility. Such experience could be a basis for the more demanding photo-ionization stripping accumulation scheme proposed here for a fusion driver. Our preliminary considerations have shown that this scheme has a large potential to reduce the overall size of a full driver.

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